Superconductivity: Cavity Design

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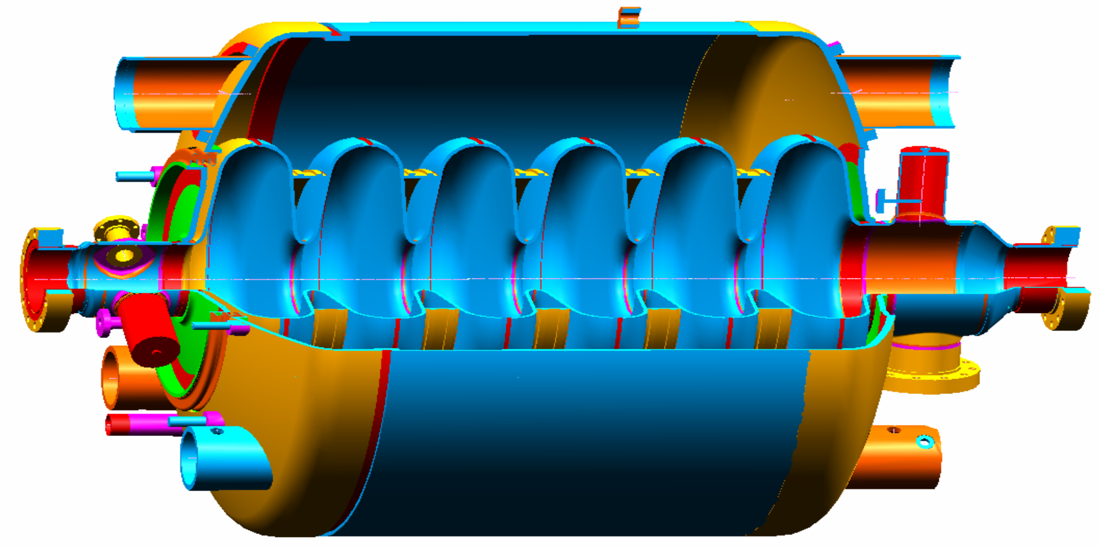
PHYSICS AT THE FARM: DISCOVERY OF THE MUON.

Outline

- Cavity design considerations
- Cavity components
- Performance limiting factors
- Comparative parameters for existing normal conducting and superconducting cavities
- Modeling examples



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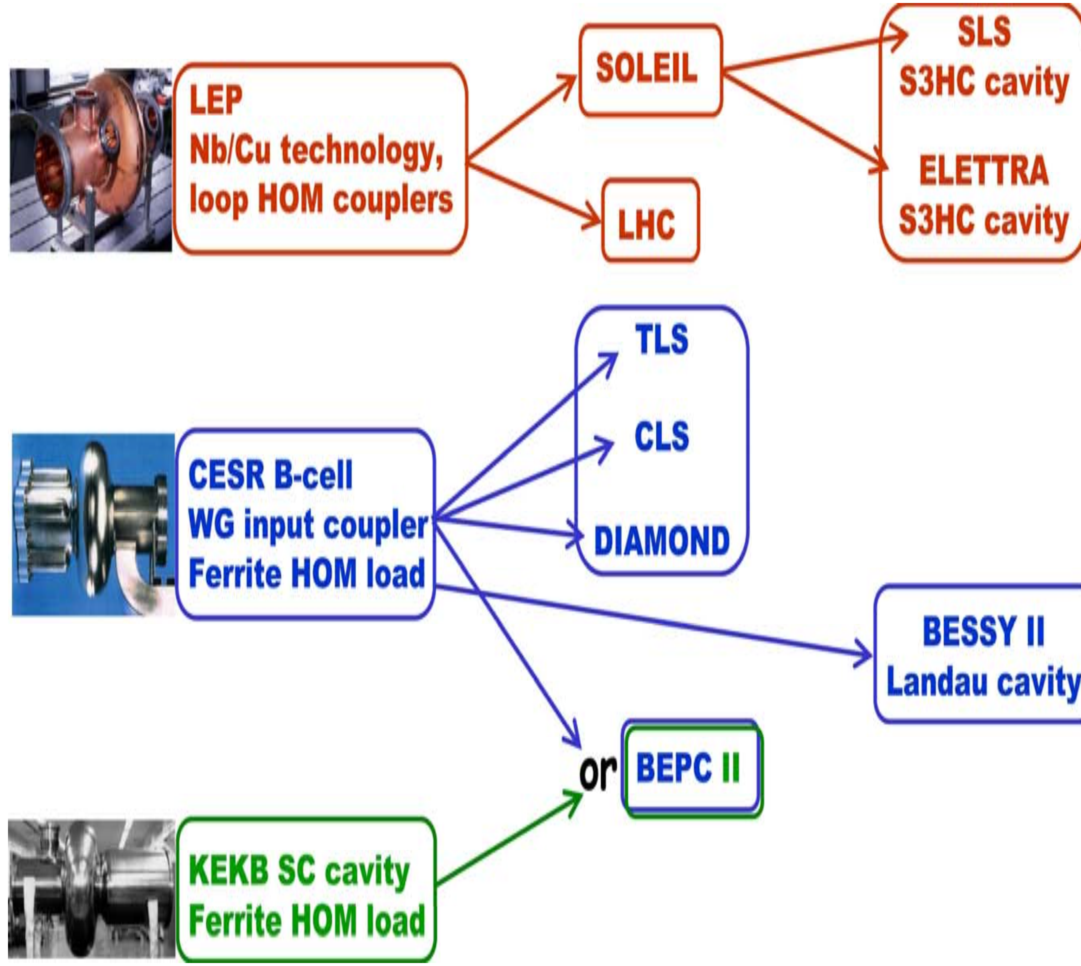
SC Accelerator history

- In 1977 Stanford completed the first SC accelerator with a 27 meter linac
- In 1982, Cornell performed the first test of an HEP SC storage ring with 1.9 MV/m gradient.
- In 1983 and 1984, CERN and KEK followed suit with 2.1 and 3.5 MV/m gradient, respectively.



SC accelerating cavities: Benefit vs. Cost

- Advantage of SC for accelerating cavities has been debated. In fact, many proposed linear electron positron colliders are based on normal conducting cavities- NLC (U.S.), JLC (Japan), CLIC (Europe). However, TESLA (Europe) uses SC.
- Arguments against SC include the low accelerating fields and the high cost of cryogenic.
  - Early gradients of only 5 MV/m were achieved
  - Max accelerating field for niobium $E_{acc} \sim 50$ MV/m
  - NC cavities at frequencies > 5 GHz could in principle achieve 100 MV/m

SC accelerating cavities: Benefit vs. Cost II

- Gradients have increased dramatically for SC cavities. Tesla cavities have now reached over 40 MV/m
- Worldwide consensus for cost of converting ac power to beam power is 2:1 in favor of SC.
- SC operates at lower frequency. Reduces negative beam / cavity interaction
  - Tesla is 1.3 GHz facility
  - NLC / JLC / CLIC > 11 GHz operating frequency
- Fewer cavities required due to higher gradients.
- Easier to detune cavity, if necessary, to make invisible to the beam.

Cavity Parameters

$$P_c = \frac{R_s}{2} \int_S H \bullet H^* dS$$

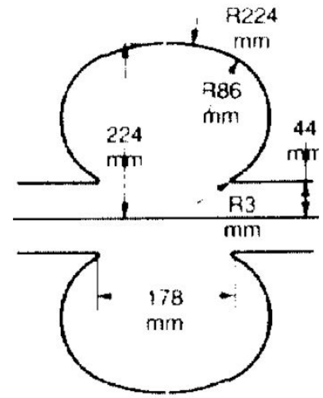
$$R_{shunt} = \frac{V_c^{\,2}}{P_c}$$

$$Q = \frac{\omega_o \mu_o}{2P_c} \int_V H \bullet H^* dV$$

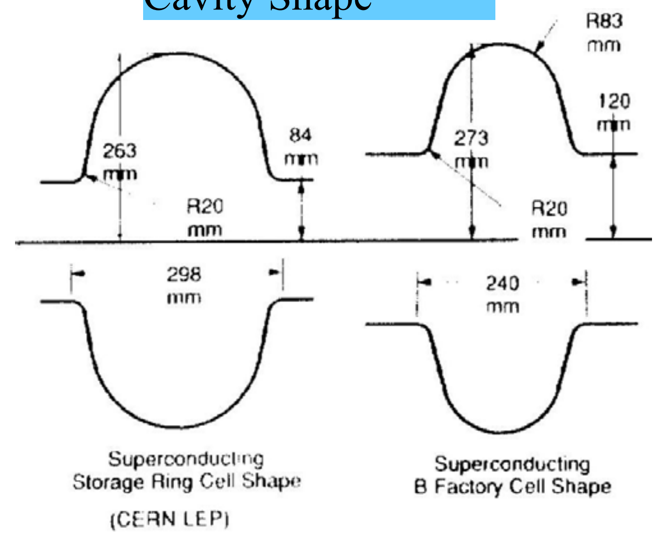
- Power loss is dependent upon surface currents on the cavity walls, the resistivity of the cavity surface, and the operating frequency.
- Shunt impedance of the fundamental mode is typically maximized in order to reduce peak surface fields and losses.
- Q is defined as a ratio of the stored energy in a cavity to the power lost along its surface.
- R/Q is a measure of the merits of a cavity design irrespective of the material properties of the cavity

Geometrical Considerations

- Cavity geometry is critical to maximize performance
- Considerations are different compared to NC cavity since power losses are much lower.
- Large beam aperture is advantageous.
  - Reduces short and long range wakefields
  - Permits HOM damping outside cavity
  - Improves field uniformity and energy coupling for multi-cell cavities
  - Reduces beam impedance



Normal Conducting Cavity Shape



Superconducting Cavity Shape

Geometrical Considerations II

- Large beam tubes have disadvantages
  - Reduces shunt impedance
  - Increases peak surface electric and magnetic field values
  - Increases refrigeration load
- Multi-cell cavities reduce system costs, fringing fields, and minimize space requirements.
- Single-cell and multi-cell cavities with a small number of cells promote field uniformity, simplifies manufacturing and reduces input coupler power handling
- Rounding cavity walls is essential to minimize multipacting.

CESR (Cornell)

LHC (CERN)

Determination of Frequency

Disadvantages of High Frequency

- Linear increase in power loss due to frequency
  - R_s is proportional to f^2, so surface resistivity increases by the square of the frequency for a given length.
  - Scaling cavity dimensions with increased frequency reduces surface area and therefore power loss by only f^{-1}.
- Longitudinal wake fields generated by the bunch scale as f^2. Transverse wake fields scale as f^3.
- Wake fields may increase beam emittance and increase cryogenic losses.
- Removal of thermal energy may be more difficult
- For very high frequencies and / or very low temperature, the anamolous skin effect increases losses

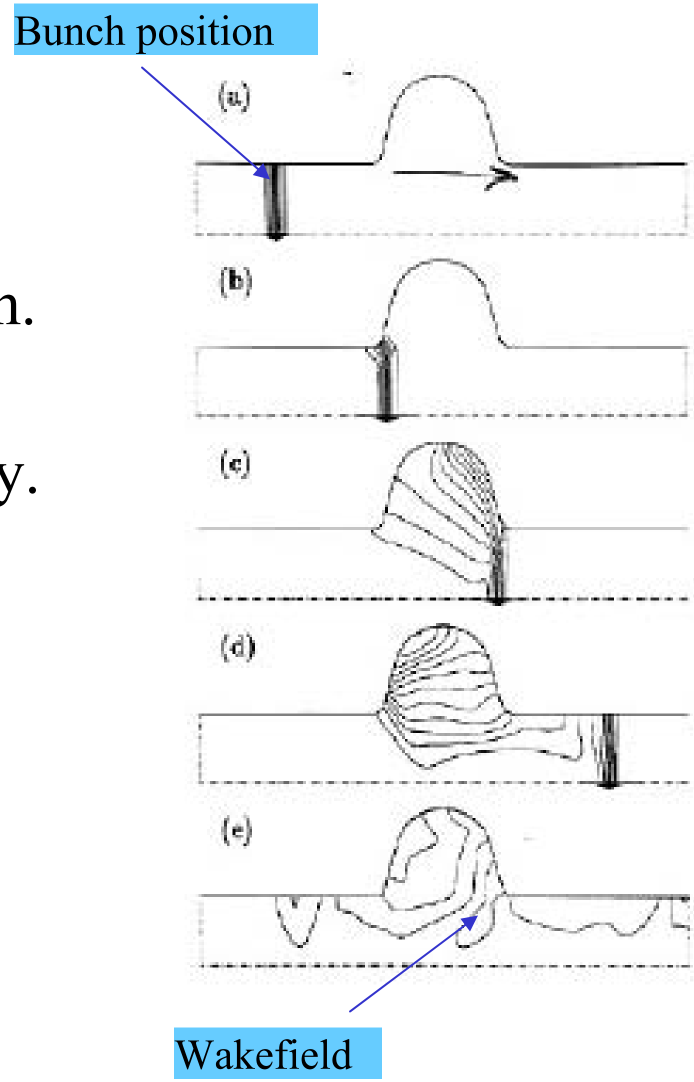
Determination of Frequency II

Advantages of High Frequency

- Smaller cavities required at higher frequency, more compact cryogenic system. As a result, entire assembly requires less space.
- Less cavity surface area reduces chance of imperfections and contamination of niobium material.
- Reduced likelihood of thermal breakdown and field emission sites.
- Less expensive for cavities and cryostat system.
- If long accelerating length required, higher frequency is necessary due to prohibitive costs.

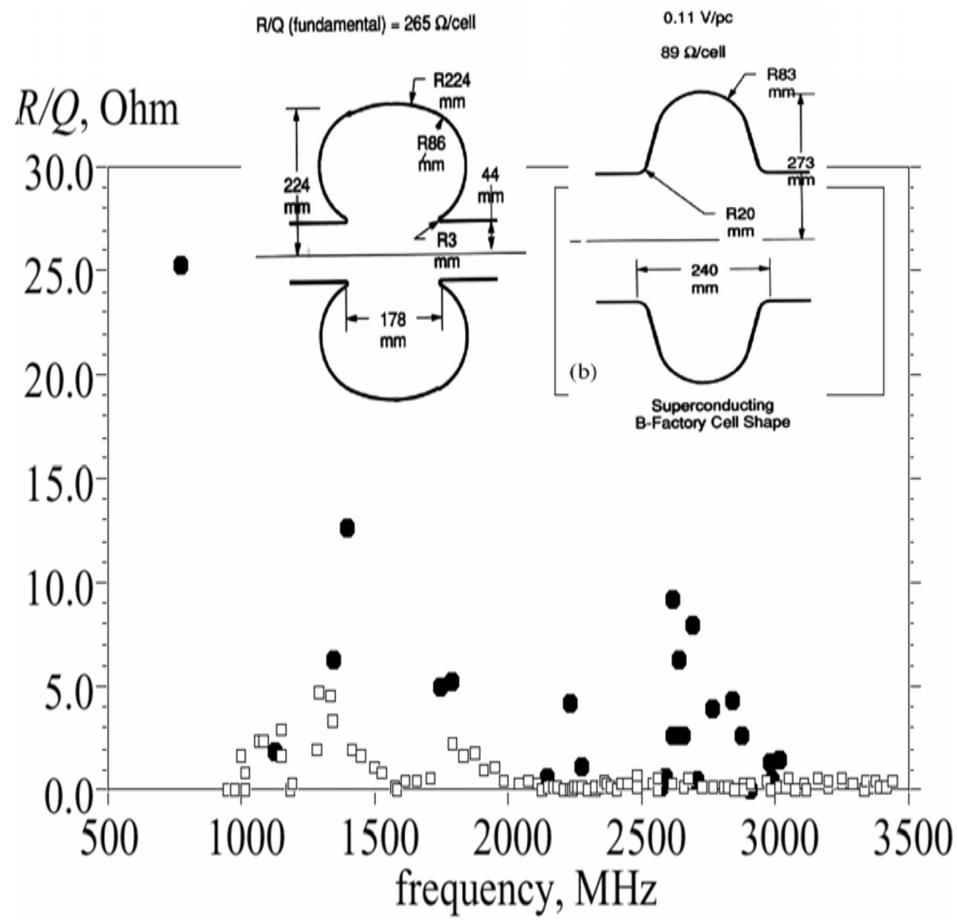
HOM Damping

- HOM's must be kept small to avoid excessive power dissipation in the liquid helium.
- HOM's do not dissipate quickly due to high Q of cavity.
- Circulating beam can become unstable due to multibunch instabilities
- Necessary to damp HOM's depending on Q of the mode and its loss factor.



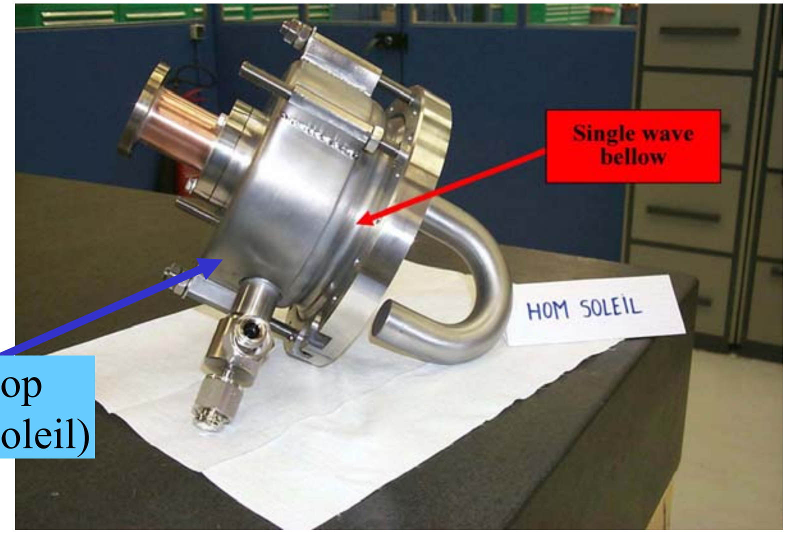
HOM Damping II

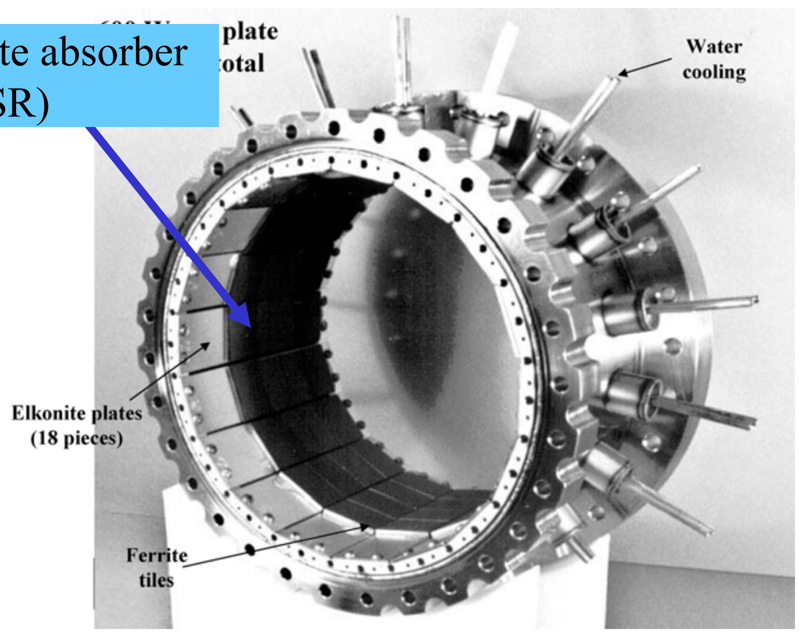
- Large beam pipes are used in SC cavities to remove HOM's from the resonant structure.
- HOM absorbers are located outside of the low temperature cryogenic environment.
- Trapped modes occur if there is little field in the end cells of a multi-cell cavity or little field near the beam pipes.
- Trapped modes are of particular concern since they would necessitate a damper in the body of the cavity which would greatly reduce the cavity Q.
- Cavity shape must be designed to avoid trapped modes.

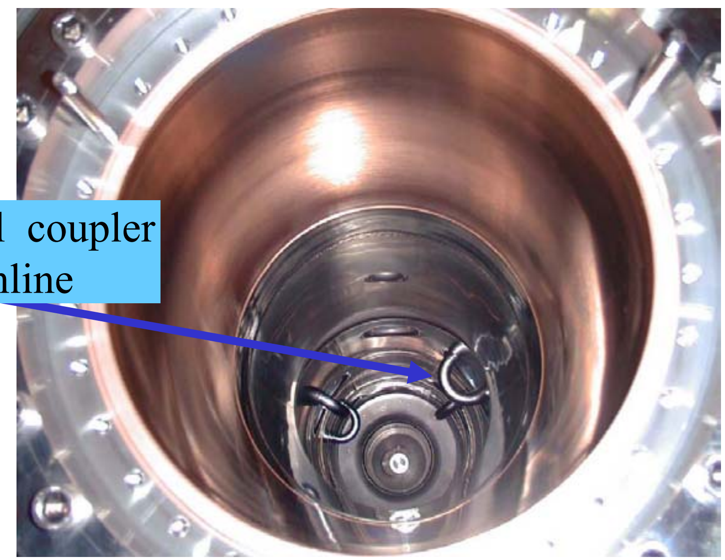


HOM Damper Designs

- Ferrite absorber material may be located in the beamline to absorb HOM’s.
- Coaxial couplers are also used to extract and transfer the HOM power to external loads

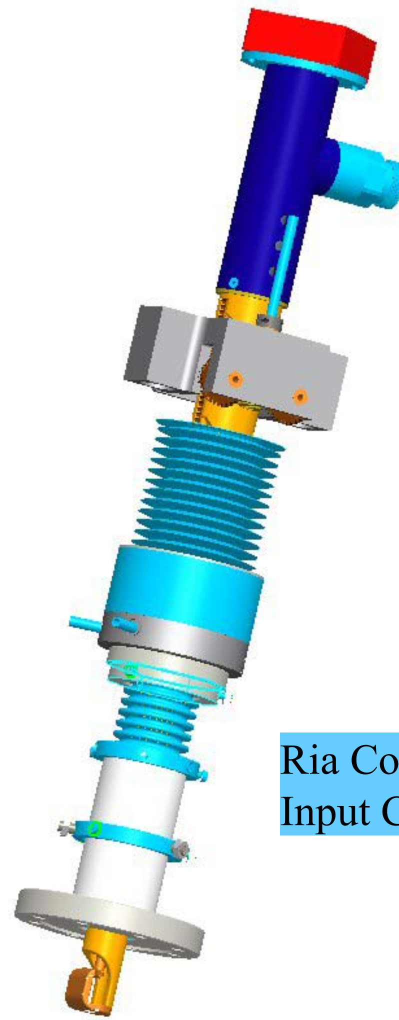






Input Coupler / Tuner Design

- Input coupler is often placed outside cavity in the beam pipe to prevent enhancement of the electric and magnetic fields and to minimize multipacting.
- Coaxial couplers are more compact and are often used in low frequency applications. They also are more suitable for variable coupling applications.
- Waveguide couplers are attractive at higher frequencies and for higher power applications since cooling is easier.
- Tuner plunger is typically not used in SC cavities due to dust generation as tuner moves. Plunger also increases the risk of multipacting.
- Tuning is achieved by mechanical adjustment of the length of the cavities (made possible by the elasticity of niobium). Fine tuning is accomplished by a piezoelectric tuner.



Ria Coaxial Input Coupler

Cavity Limiting Issues: Surface Magnetic Field

- Magnetic field along the niobium surface can not exceed its critical values before changing state.
- B_{c1} is the value at which niobium changes from a type I to a type II SC, while B_{c2} is the value where niobium is no longer a type II superconductor and becomes NC.
- The thermodynamic critical field B_c is the limiting value for SC operation. It precedes B_{c2}. Magnetic fields of this strength force a transition to NC.

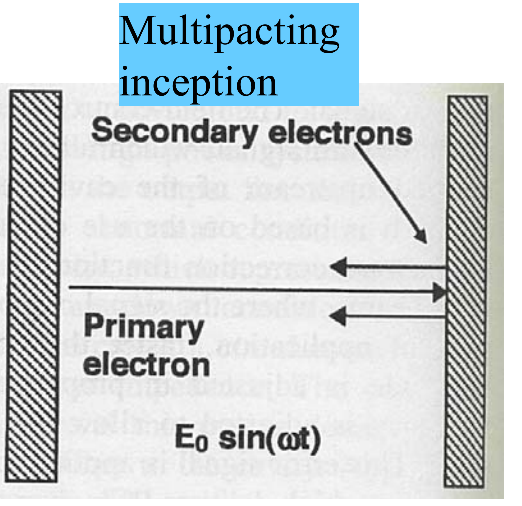
	B-Field
B_{c1}	160 mT
B_c	190 mT
B_{c2}	300 mT

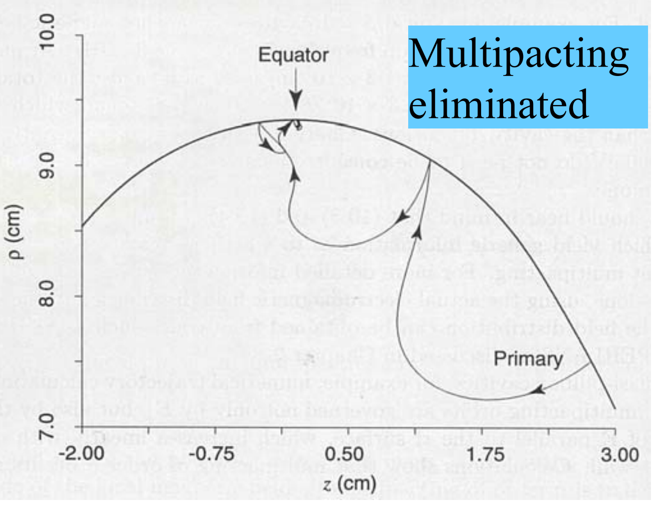
Critical field values for niobium at 2 K

- The maximum practical magnetic field limit appears to be close to Bc
- Maximum accelerating field given the constraints on the magnetic field is approximately 50 – 55 MV/m

Cavity Limiting Issues: Multipacting

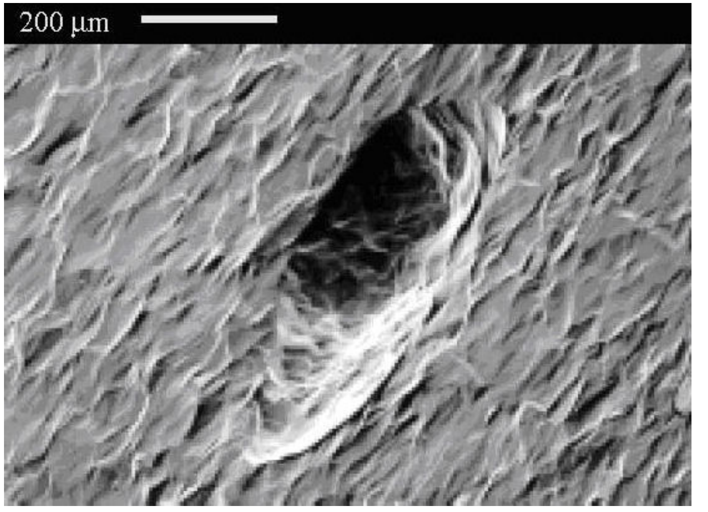
- Multipacting occurs when an electron is emitted from a surface, impacts another surface thereby freeing other electrons.
- It is a resonant process which builds up a large number of electrons that continuously absorb rf power
- At some point it is impossible to raise the gradient since all the increased rf power is being absorbed by the avalanche of electrons.
- Multipacting severely limited the ability of SC cavities to raise their gradient prior to the mid 1980's.
- For velocity of light structures, multipacting is no longer a significant problem since the appropriate cavity shape has been discovered.

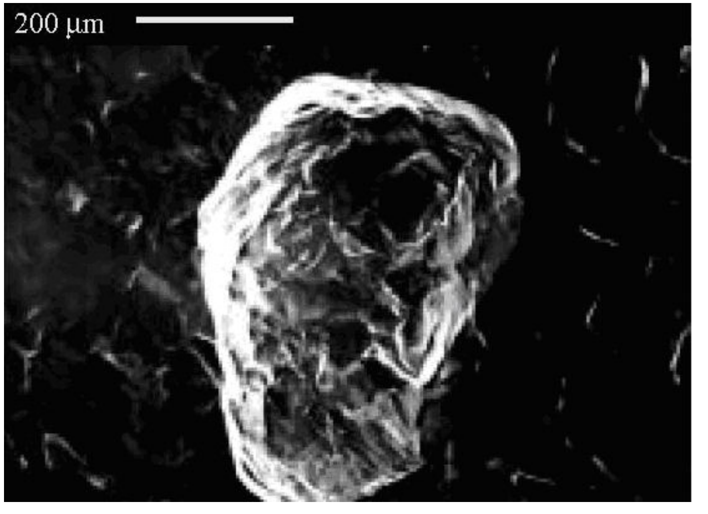




Cavity Limiting Issues: Field Emission

- Unlike the magnetic field, there is no theoretical limit for the maximum electric field.
- Electric surface field gradients of 220 MV/m have been achieved.
- Field emission is the chief limiting factor for the surface electric field.
- Emission of electrons from high electric field regions can cause thermal breakdown.
- Emission sites are created by contaminants on the cavity surface which result in protrusions that enhance the electric field thereby initiating electron emission.

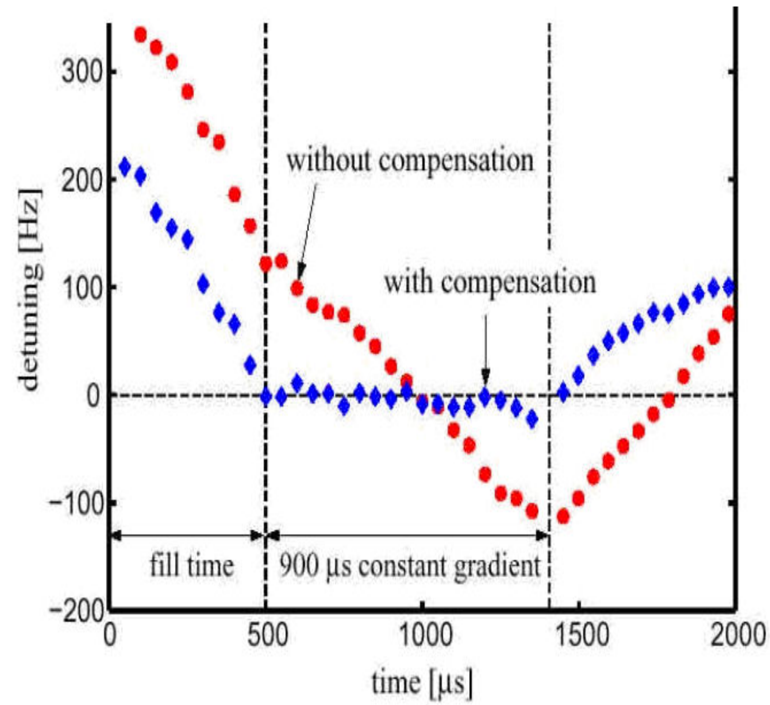




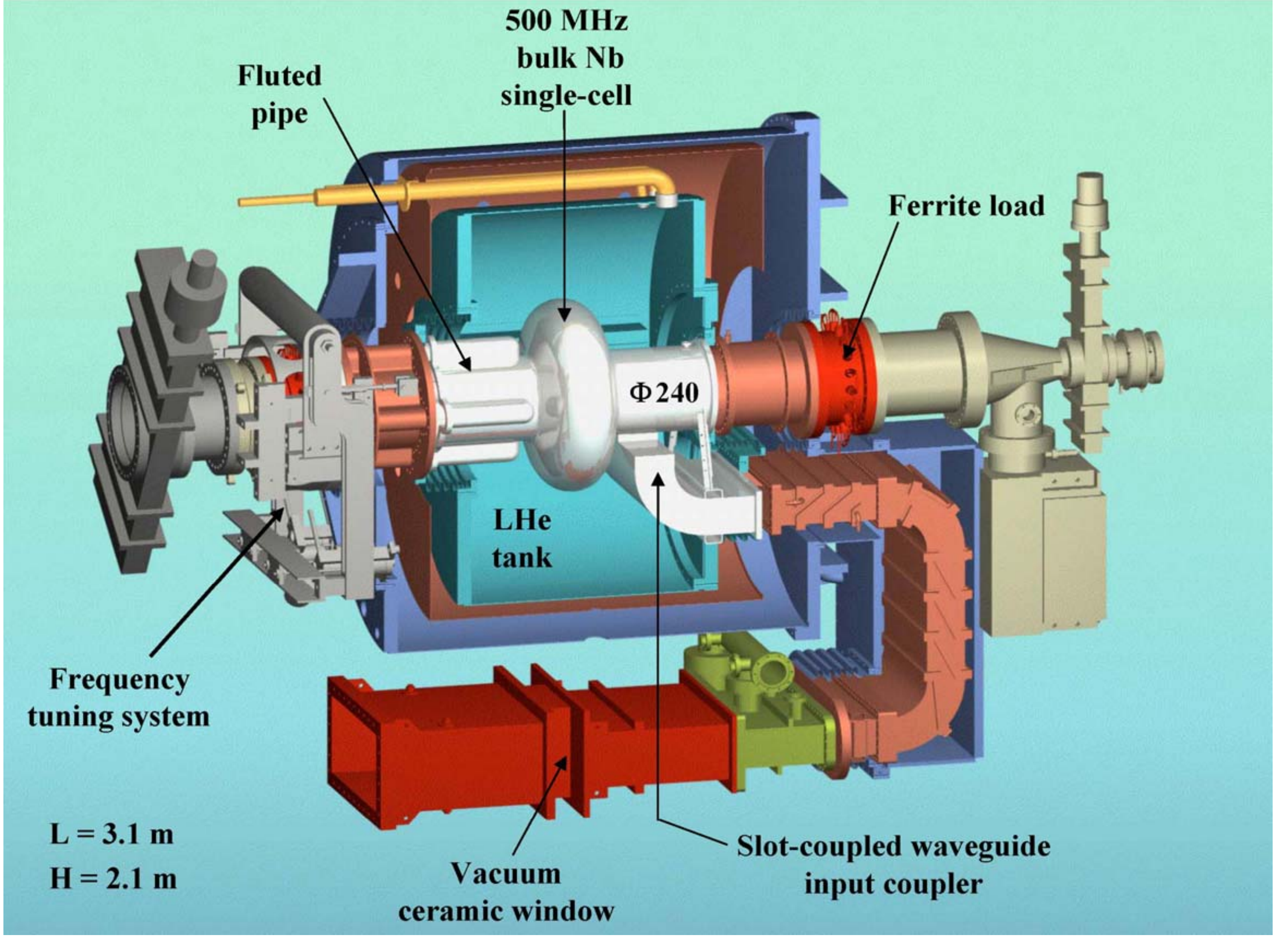
Cavity Limiting Issues: Frequency Stability

- Bandwidth of an unloaded SC cavity is on the order of 0.1 to 1.0 Hz
- Cavity loading reduces the Q to on the order of $10^5 - 10^6$ which still results in a narrow bandwidth.
- Microphonics is where the cavity is subject to mechanical vibrations. This shifts the cavity off resonance and requires much greater rf power.
- RF control system must reduce cavity amplitude and phase jitter. Also, cavity stiffening may help alleviate the problem.
- Lorentz force perturbs the frequency due to the deformation of the cavity walls from the force created by the cavity surface magnetic field on the surface current.
- Piezo-electric tuner is often used to compensate for frequency shift.

Lorentz Force detuning



System Design: CESR Cryomodule (500 MHz)



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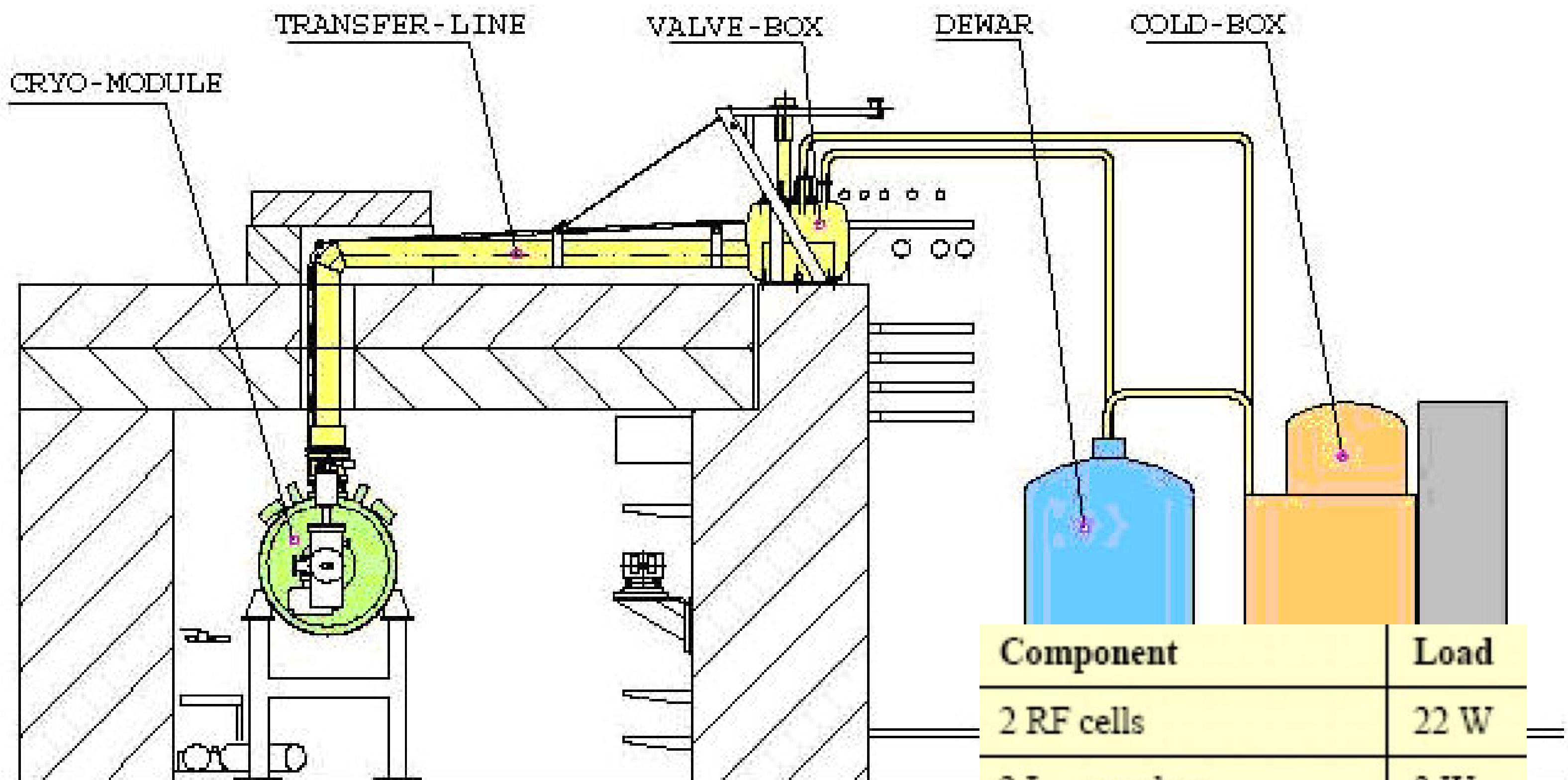
System Design: CESR-Type Cryomodule Installation

System Design: Cryosystem Layout



Component	Load
2 RF cells	22 W
2 L – couplers	3 W
4 T – couplers	8.5 W
2 Extremity tubes	0.2 W
Cryomodule static losses	5.1 W
Transfer-lines	6.5 W

- Dewar and cold-box are located in a separate building to isolate the cryosystem and cavities

Modeling: Analytic Solution of Pillbox Cavity

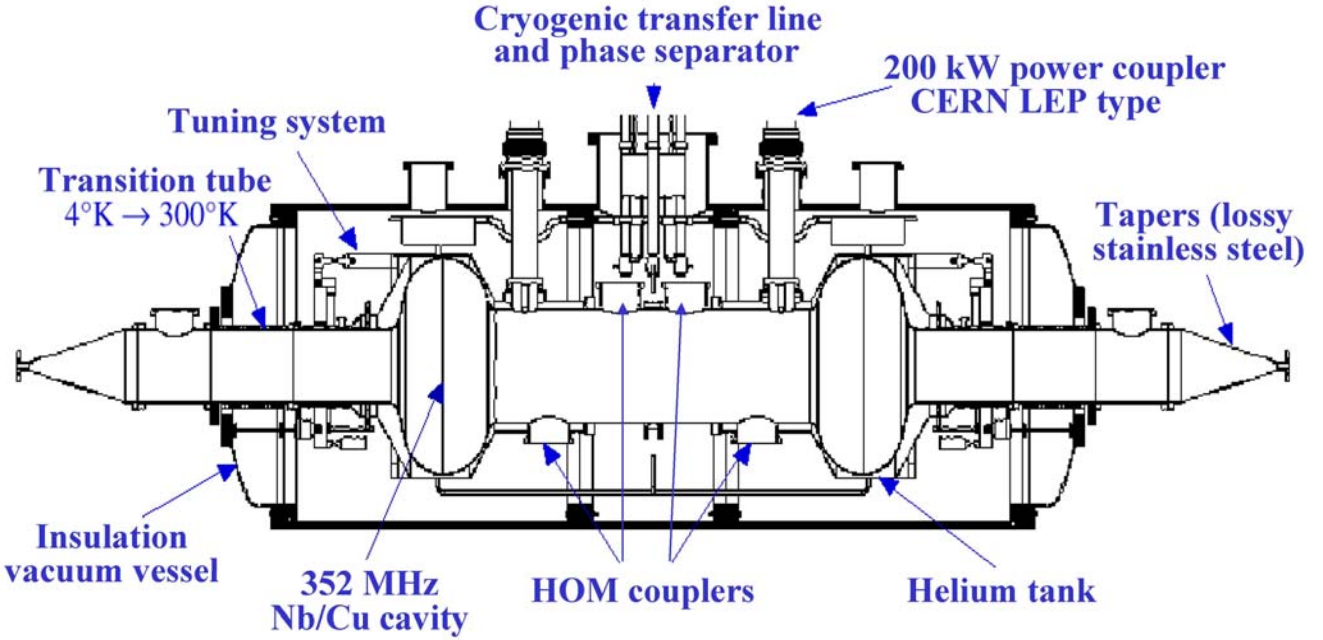
- Typical surface impedance for a normal conductor is on the order of mΩ while for a superconductor it is nΩ.
- Peak surface fields are well below dangerous levels for niobium.
- P_{tot} is the total required ac power for cavity losses. Included is refrigeration for SC cavity and Cu losses and 0.5 klystron efficiency factor for NC cavity.

	NC	SC
Freq	1.5 GHz	1.5 GHz
R_s	10.1 mΩ	20 nΩ
P_c	200 kW	0.4 W
U	0.54	0.54 J
Q	$25 * 10^3$	$13 * 10^9$
R_{shunt}	$5.0 * 10^6$	$2.5 * 10^{12}$
R_{shunt}/Q	200 Ω	200 Ω
E_{pk}	15.7 MV/m	15.7 MV/m
H_{pk}	30.5 mT	30.5 mT
P_{tot}	~ 400kW	300 W

Parameters for a 1.5 GHz resonant pillbox cavity with a 1 MV gap voltage and a 10 MV/m gradient

Performance Comparison: APS vs. Soleil SC cavity

- Soleil uses 352.2 MHz single-cell superconducting cavities in a 354 meter storage ring. It is a 3rd generation synchrotron light source operating at 2.75 GeV.
- A direct comparison can be made between the APS and Soleil cavities comparing performance at identical frequencies for velocity-of-light accelerators.



Performance Comparison: Cavity Parameters

- R/Q geometry factor is substantially reduced for Soleil cavity as compared with APS
- Since Q is large the inferior geometry factor is not important

	APS	APS Simulation	Soleil
Freq (MHz)	351.9	350.3	352.2
Q	$49 * 10^3$	$52 * 10^3$	$2 * 10^9$
R_{shunt}	$11.2 * 10^6$	$11.8 * 10^6$	$9.0 * 10^{10}$
R_{shunt}/Q	230	230	45
P_c @ 1.0 MV $^+$	89.3 kW	82.6 kW	~ 8.0 W
P_c @ 4.0 MV $^{++}$	1.4 MW	1.3 MW	~ 120 W

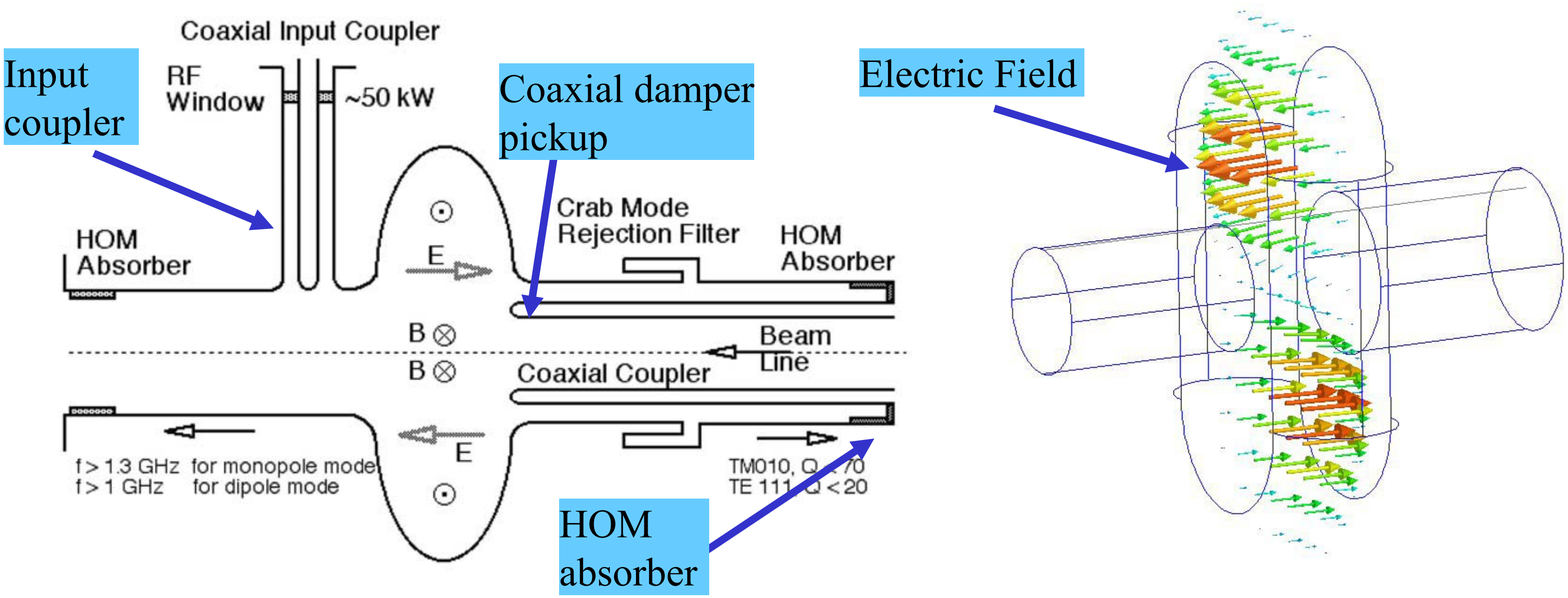
Normal conducting Aps single cell cavity compared with superconducting Soleil cavity

$^+$ Maximum theoretical voltage across cavity gap at APS

$^{++}$ CW operating voltage for Soleil cavity

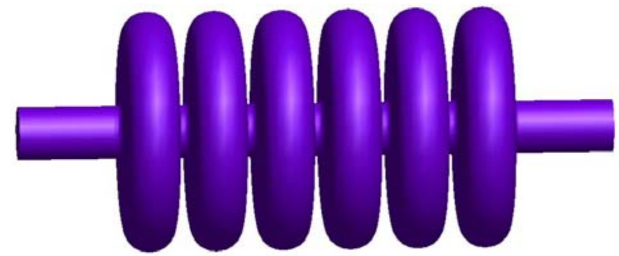
Modeling: Deflecting cavity at KEK-B

- KEK deflecting cavity utilizes the TM_{100} mode to deflect the bunch in the transverse direction. Requires 1.44 MV voltage, or < 3.5 MV/m.
- Coaxial and beam line dampers are both used to eliminate HOM's.
- Enlarged beampipe allow extranction of HOM's to beam line damper
- Coaxial coupler extracts fundamental as TEM mode. Higher frequency modes propagate as TE modes and are eliminated.



Modeling: Deflecting Cavity Proposal at APS

- Single-cell and 6-cell cavities are evaluated.
- Loss for SC single-cell cavity is approximately 250 W. RF loss for NC cavity is on the order of 10 MW.
- SC power loss and maximum field intensities in single-cell cavity are impractical for SC system.
- 6-cell cavity distributes losses and reduces maximum surface fields. Cell length has been modified in order to phase the cavity fields with the particle velocity.
- Decreased field gradients are due to higher transverse shunt impedance (R_T/Q) which improves high gradient Q degradation.
- Power dissipation per cavity is less than 10 W.



	1-Cell	6-Cell
V_T	4 MV	4 MV
Cell Length	7.4 cm	10.7 cm
R_T/Q	71.7 ς	393.9 ς
Q	$1.0*10^9$	$1.0*10^9$
P_L	223 W	40.7 W
P_L/cell	223 W	6.8 W

Table 3: APS 1-cell and 6-cell deflecting cavity parameters.

Modeling: Deflecting Cavity Proposal at APS II

- Maximum allowable magnetic flux density for SC cavity is roughly 100 mT to ensure adequate safety margin.
- An excessive B_{MAX} causes local heating that exceeds the cooling capabilities of the system.
- B_{MAX} was reduced from 348 mT in the 1-cell cavity to 110 mT in the 6-cell cavity.
- Further reduction in peak surface fields will likely necessitate more accelerating cavities and an improved cavity design.

	1-Cell	6-Cell
V_T	4 MV	4 MV
B_{MAX}^{+}	348 mT	110 mT
E_{MAX}^{**}	105 MV/m	19 MV/m
V_T/B_{MAX}	11.5 kV/mT	36.4 kV/mT
V_T/E_{MAX}	0.04 m	0.215 m
E_{MAX}/H_{MAX}	380 V/A	215 V/A

Table 4: APS Deflecting cavity peak fields.

$^{+}$ B_{MAX} is peak surface B-field

** E_{MAX} is peak volume E-field